



Novel anode based on sulfonated polysulfone for medium temperature direct methanol fuel cells



Florian Mack^{*,1,3}, Viktor Gogel, Ludwig Jörissen, Jochen Kerres²

Centre for Solar Energy and Hydrogen Research Baden-Wuerttemberg, Division 3, Electrochemical Energy Storage and Conversion, Helmholtzstr. 8, D-89081, Germany

HIGHLIGHTS

- ▶ Sulfonated polysulfone was used as ionomer in a DMFC anode at 130 °C
- ▶ The sPSU based anode has a high activity for the methanol oxidation.
- ▶ The anode has a good mechanical stability and adhesion on the Nafion[®] membrane.
- ▶ Anode catalyst inks based on sPSU do not require toxic and flammable solvents.

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ABSTRACT

Preparation of well performing electrodes using non fluorinated polymer electrolytes is a challenge due to the transport properties of the ion conducting polymer as well as due to the solvents involved. Polymer perfluorinated sulfonic acids such as Nafion[®] are possible solvable as ionomer in the DMFC anode catalyst layer by concentrated methanol solution at temperatures above 100 °C; therefore more stable polymers are necessary. In this work, we studied the conditions to use sulfonated polysulfone (sPSU) as an ionomer in the anode of a direct methanol fuel cell (DMFC) operating at a temperature of 130 °C.

For preparing catalyst dispersions, toxic and flammable solvents were substituted by water using the harmless surfactant Triton X-100 as an additive. As a result the preparation of the catalyst inks and MEAs was accelerated and simplified. The sPSU based anodes showed quite high performance for the methanol oxidation especially in a half cell. The best results were obtained with an anode catalyst layer containing 5% sPSU prepared from a water based ink containing 2% sPSU and 20% Triton X-100 sprayed on a Nafion[®] 115 membrane.

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1. Introduction

Direct methanol fuel cells (DMFC) are promising electrochemical power sources, especially for portable power generators. Advantages are the high energy density of methanol and the simple system design of liquid-feed fuel cells [1,2]. The DMFC avoids complex fuel reforming [3] by direct electrochemical oxidation. However, the performance of DMFCs is still too low for successful commercialisation in high power applications. This is mainly related to slow anode kinetics and high permeation of methanol and water through the membrane, the latter causing the formation

of a mixed potential as well as mass transport limitations at the cathode.

It is well known that anode kinetics can be improved significantly at higher operating temperatures [4]. Fuel and water transport to the cathode are determined by the electrolyte membrane.

The class of materials most widely used as electrolyte membranes and ionomers providing ionic conductivity in the electrodes are polymer perfluorinated sulfonic acids such as Nafion[®]. These materials are expensive; furthermore, the Nafion[®] polymers as membrane and especially as electrode ionomer (recast film) are soluble in aqueous methanol solutions at high temperatures and methanol concentrations [5,6].

In addition, the water and methanol crossover through Nafion[®] membranes increases at higher temperatures [7] and reduces the performance of the cell even further. Since the membrane electrode assembly (MEA) properties are crucially influencing the cell performance, new materials are required, particularly novel

* Corresponding author.

E-mail addresses: florian.mack@uni-ulm.de, florian.mack@kit.edu (F. Mack).

¹ Permanent address: Helmholtz Institute Ulm, Helmholtzstr. 8, D-89081, Ulm, Germany.

² Permanent address: Institute of Chemical Process Engineering, University of Stuttgart, Boebingerstr. 72, D-70199 Stuttgart, Germany.

³ <http://www.zsw-bw.de>

membranes and ionomers. Processing these materials into high performance MEAs is a key challenge for further DMFC development [1,8].

Different polymers were investigated as alternative to Nafion® for DMFCs with working temperatures above 100 °C [9–12]. They typically are less expensive [13] and show reduced methanol crossover [14] as compared to Nafion®. However, electrode adhesion to the alternative membranes normally is bad when Nafion® is used as an ion conducting electrode additive. Electrode adhesion can be improved when the ion conducting electrode additive is selected from the same class of polymers being used as the electrolyte membrane [14–16].

However, MEAs based on alternative ionomers often show low power density [17], due to the lower conductivity of the ionomers as compared to Nafion® as well as inferior transport properties for reactants. In addition, the non PFSA ionomer solutions are containing toxic and highly flammable solvents that can damage the membranes [18–20]. Furthermore, the solvents typically used for non PFSA-ionomers are remaining partly in the electrodes due to their boiling point thus decreasing the free pore volume [21,22] and potentially interfering with the catalysts.

In this work the proton conductivity of sPSU comprising a mean SO₃H group content of 1 SO₃H group per repeat unit, a non fluorinated ion conducting polymer (see Fig. 1), and Nafion® is compared by an in situ high frequency impedance measurement. SPSU was dispersed in water or an aqueous solution of the harmless surfactant Triton X-100. Anodes with sPSU respectively Nafion® as ionomer and MEAs based on these anodes are electrochemically characterized (activity, performance, methanol crossover).

2. Experimental

The materials used in this study are listed in Table 1.

2.1. Preparation of the ionomer solutions and catalyst ink

Catalyst dispersions containing alcohols or other flammable solvents are considered to be hazardous due to the possibility of ignition during the spraying process. In addition, the frequently used organic solvents like *N*-Methyl-2-pyrrolidone (NMP) are toxic. Therefore, non flammable, non toxic, water based sPSU suspensions were developed using Triton X-100 as dispersant.

For a 2% sPSU suspension in an aqueous 10% Triton X-100 solution, 0.98 g Triton X-100 was dissolved in 8.82 g water by magnetic stirring and then 0.2 g small sPSU pieces were added. This composite was treated in an ultrasonic bath for 5–10 h like described in Ref. [23] until a clear suspension resulted. For the reference measurements, commercially available 15% Nafion® solution was used.

For the anode inks, 0.5 g PtRu black (Johnson Matthey HISPEC 6000) was dispersed in 5 g millipore water. Subsequently, the ionomer solutions were added. The cathode was prepared from 40% Pt/C (Heraeus). The Nafion® containing inks were stirred magnetically for at least 3 days, the inks with sPSU at least 12 h.

Table 1

List of used materials.

Material	Delivered from	Function
Nafion® 115	Ion power	Membrane
sPSU	ICVT ²	Ionomer
Nafion® solution (15 wt%)	C.G. Processing, Inc.	Ionomer
PtRu black	Johnson Matthey	Anode catalyst
40% Pt/C	Heraeus	Cathode catalyst
Hydrogen peroxide	Sigma Aldrich	Membrane pre-treatment
Sulphuric acid	Sigma Aldrich	Membrane pre-treatment
Triton X-100	Sigma Aldrich	Additive/dispersing agent
Sigracet 10BB	SGL carbon	GDL

2.2. MEA preparation

Nafion® 115 membranes were conditioned by boiling in 3% H₂O₂ in order to remove organic contaminants followed by successive boiling in millipore water, 0.5 M sulphuric acid and a second time in millipore water each time for 1 h.

Wet Nafion® 115 membranes were fixed in an aluminium frame covered by a polymer foil and dried at 80 °C in an oven. The catalytic layers were prepared by spraying of the catalyst inks in multiple layers directly onto the polymer electrolyte membrane at a substrate temperature of 100 °C. The catalyst loading was determined by weighing the dried MEA. The anode loading was defined as 3 mg cm⁻² PtRu, the cathode loading as 1 mg cm⁻² Pt.

2.3. Electrochemical characterization

The MEA investigations were carried out in home-made gold-plated stainless steel cells having a single channel serpentine flow field of the dimensions 1 mm × 1 mm. Teflonized carbon paper (SGL 10 BB) was used as gas diffusion layers. The cell used for performance studies had an active area of 5 cm × 5 cm while the cell used for impedance studies had an active area of 1 cm × 1 cm. The test station for the single cell DMFC measurements was described before in Ref. [7]. Two potentiostats (Zahner IM 6, Zahner PP 241) were used for the electrochemical measurements.

Half-cell and full cell configurations have been used. In the half cell setup the anode was fed with 1 M methanol solution at a flow rate of 6 mL min⁻¹. The cathode was fed with 50 mL min⁻¹ hydrogen at atmospheric pressure to make a reversible hydrogen electrode (RHE). In the full cell setup the anode was fed with 1 M methanol solution while the cathode was fed with air. Methanol crossover was measured by CO₂ release from the cathode as described in Ref. [24].

The membrane impedance was measured as a function of temperature and methanol concentration in a full cell setup (Fig. 2). The membranes were positioned between 2 GDLs (SGL 10 BB) and put in a full cell with 1 cm² active area. To simulate anode conditions, the cell was supported with 4 mL min⁻¹ water or methanol solution on both sides of the membrane to simulate the fully hydrated conditions in the anode.

The “anode outlet” was directly connected to the “cathode inlet”. The cell pressure was set to 2.8 bar abs. The cell impedance was measured in the kHz-range at a phase angle of zero by variation of frequency. Before the measurement, the cell was

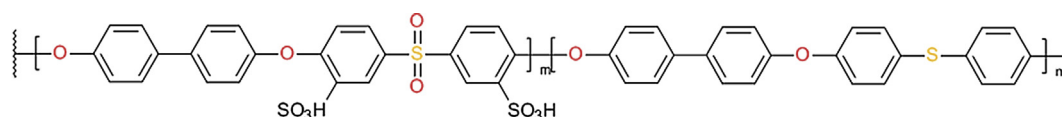


Fig. 1. Structure of the used sPSU, ($m/n = 1/1$).

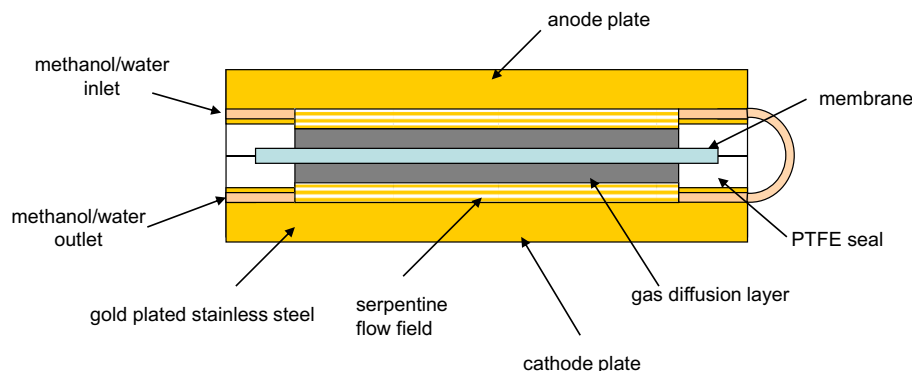


Fig. 2. Full cell setup layout for impedance measurements.

conditioned by heating to 130 °C with two-sided water supply. The cell temperature (25–130 °C) and methanol concentration (1–4 M) were varied. Steady state values were recorded.

Methanol adsorption on the PtRu anode catalyst was studied by methanol stripping cyclic voltammetry (CV) as described in [3]. Before starting the methanol stripping the cell was flushed with deionised water and CVs were performed from 0 to 800 mV vs. RHE until the result was stable. The peak in the range of the methanol oxidation served as baseline for the determination of the methanol oxidation peaks. Subsequently, methanol was adsorbed at a potential of 0 V vs. RHE from 1 M aqueous methanol solution during 5 min followed by flushing the cell with deionised water for 30 min. Three cycles were recorded with a scan rate of 10 mV s⁻¹ by cycling the electrode potential from start potential to 800 mV at cell temperatures of 25–130 °C. The active anode area was calculated from the first peak. At higher cell temperatures the methanol oxidation started at lower potentials and they were 250, 180, 100 and 0 mV for the T_{cell} = RT, 40, 80 and 130 °C corresponding. All potentials were IR-corrected.

Voltage–current curves were measured galvanostatically at 130 °C with 2.8 bar anode pressure and 4 bar cathode pressure absolutely. The current was held for 2 min before the voltage was recorded. For this measurement the cell with an active area of 25 cm² was used. The stoichiometry factor for methanol was fixed at $\lambda = 2$ and for air at $\lambda = 4$. Before the measurement, the cell was conditioned potentiostatic at cell voltage 0.4 V and at $T = 130$ °C about 8–10 h.

Polarization curves were measured in the half-cell setup by manually electrode potential variation in the potential range between resting potential and 500 mV.

2.4. Physical characterization

All important parameters of the sPSU and Nafion[®] ionomer were obtained by measuring the corresponding membranes similar to that in Ref. [25]. Water uptake and swelling of the membranes were determined by measuring the change in weight and dimensions between dry and wet conditions at 25 °C. Membranes with 1 cm × 1 cm in the dry state were used for this measurement. The

membrane density was calculated by the measured weight and volume of the dry membranes.

Surface and cross-sectional morphologies of the anodes and MEAs were investigated with scanning electron microscopy (Zeiss LEO 1530 VP). The MEA cross-sections were made by submerging the MEAs in liquid nitrogen and then fracturing.

3. Results and discussion

3.1. Ionomer characterisation

Density, water uptake and swelling of sPSU and Nafion[®] as membrane at 25 °C are compared in Table 2. The density of sPSU is lower than Nafion[®]; however, its water uptake and swelling are significantly higher.

An important property of the ionomers is their proton conductivity. In Fig. 3 the temperature dependence of the specific impedance of the sPSU and Nafion[®] membranes is shown.

The conductivity of sPSU at 130 °C is 60% higher than for Nafion[®]. The conductivity of both polymers was found to be above values determined in ex-situ measurements [25]. The specific conductivity of Nafion[®] increases more as 2 times with temperature, but the sPSU conductivity shows only very weak temperature

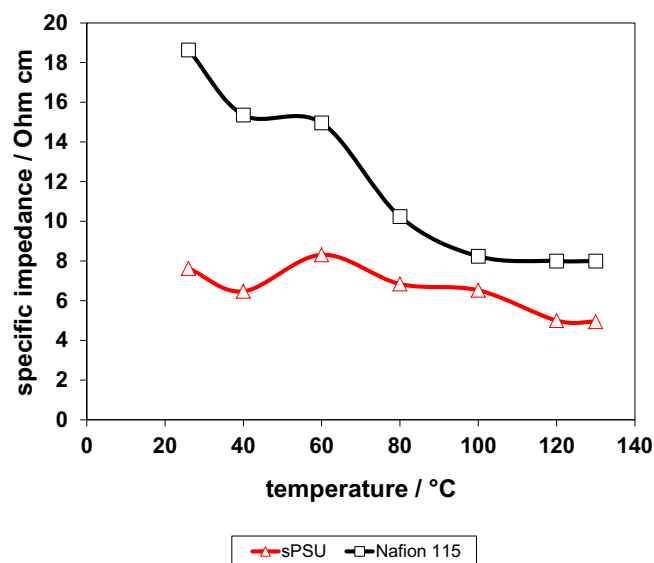


Fig. 3. Temperature dependence of the specific impedance of Nafion[®] and sPSU. $A = 1$ cm², anode/cathode: GDL: SGL 10BB, $F_{\text{H}_2\text{O}} = 4$ mL min⁻¹, $p = 2.8$ bar.

Table 2

Density, water uptake and swelling of sPSU and Nafion[®], $T = 25$ °C.

	Density, g cm ⁻³	Water uptake, mass %	Swelling, vol. %
Nafion [®]	1.8	11	15
sPSU	1.17	39	59

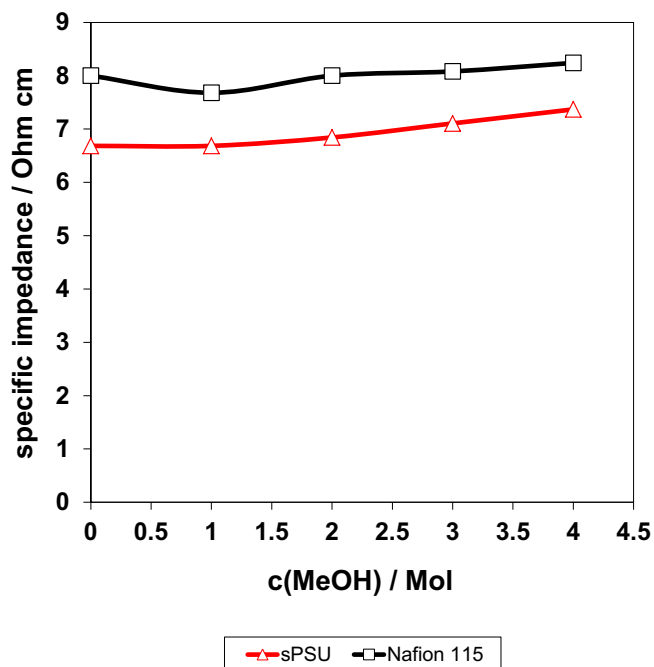


Fig. 4. Influence of the methanol concentration on the specific impedance of Nafion® and sPSU. $T = 130^\circ\text{C}$, $A = 1\text{ cm}^2$, anode/cathode: GDL: SGL 10BB, $F = 4\text{ mL min}^{-1}$, $p = 2.8\text{ bar}$.

dependence. We attribute this phenomenon to the higher water content of sPSU even at room temperature (see Table 2). The differences in temperature behaviour might be explained by differences in the polymer structure: Nafion® has a more elastic structure; while the structure of sPSU is more rigid due to its aromatic backbone leading to less elasticity than it is the case at Nafion®.

The influence of the methanol concentration on the specific impedance of sPSU and Nafion® was investigated at 130°C using 1–4 M methanol solution. The impedance of both ionomers slightly rises with increasing methanol concentration (Fig. 4), but the sPSU resistivity remains significantly lower as compared to Nafion® in the total methanol concentration range. Apparently, methanol hinders the proton mobility in the aqueous phase of the nano pore system of both membranes.

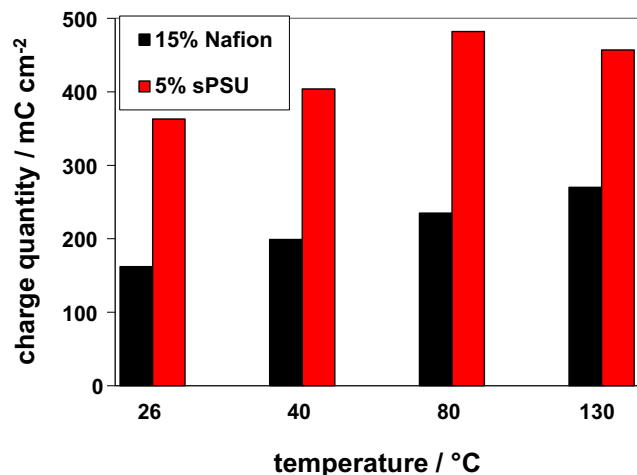


Fig. 5. Charge quantity of the methanol oxidation. $A = 25\text{ cm}^2$, anode: 1 M MeOH, 4 mL min^{-1} , $p_a = 2.8\text{ bar}$, half cell setup.

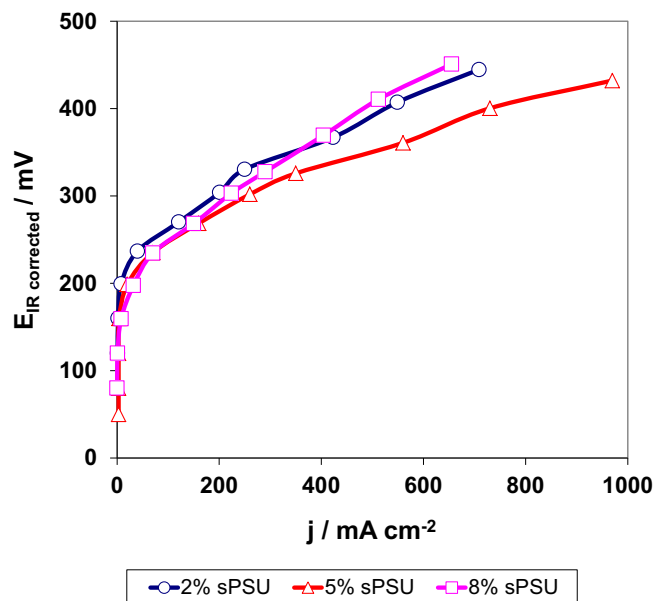


Fig. 6. Polarisation curves of anodes with different sPSU ratio. $T = 130^\circ\text{C}$, $A = 1\text{ cm}^2$, Nafion® 115 membrane, anode: 1 M MeOH, 4 mL min^{-1} , $p_a = 2.8\text{ bar}$, half cell setup.

3.2. Active area and charge quantity

The anode active area on the Nafion® 115 membrane for the methanol oxidation was determined by methanol stripping experiments. The ionomer content in the electrodes supports the formation of the three-phase boundary. Ionomers can absorb methanol from the solution and ease its adsorption on the catalyst surface. The ionomer is acting simultaneously as a buffer and a barrier for methanol. Furthermore, it interacts with the catalyst surface. To quantify the anode active area, the charge of the methanol oxidation was measured. Anodes with sPSU respectively Nafion® are compared in Fig. 5.

The methanol oxidation charge of the anodes increases with temperature and for the anode containing 5% sPSU it is 70–120%

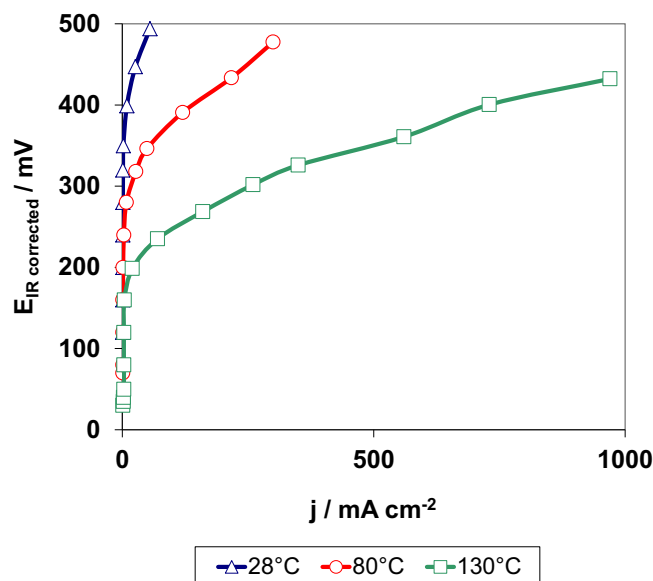


Fig. 7. Temperature dependence of the activity of an anode based on 5% sPSU. Nafion® 115 membrane, $A = 25\text{ cm}^2$, anode: 1 M MeOH, 4 mL min^{-1} , $p_a = 2.8\text{ bar}$, half cell setup.

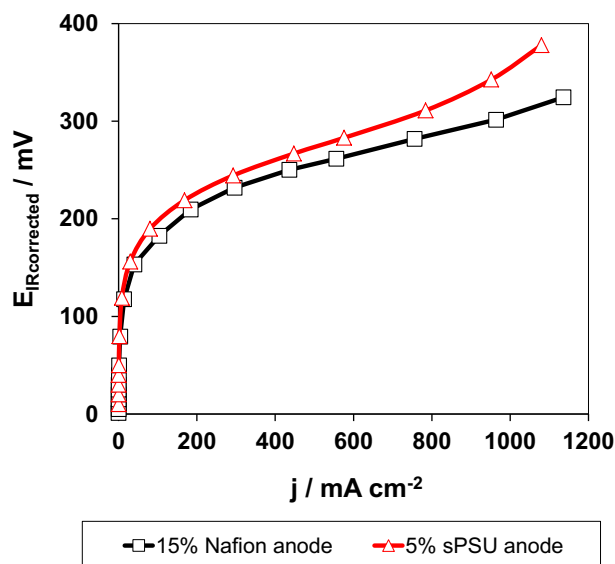


Fig. 8. Activity of anodes based on 5% sPSU or 15% Nafion®. $T = 130\text{ }^{\circ}\text{C}$, $A = 25\text{ cm}^2$, Nafion® 115 membrane, anode: 1 M MeOH, 4 mL min^{-1} , $p_a = 2.8\text{ bar}$, half cell setup.

higher than for the anode with 15% Nafion®. Apparently, the blocking of the catalyst by sPSU is reduced as compared to Nafion®.

3.3. Optimal sPSU content in the anode

The volumetric proportion of pores, catalyst and ionomer is of great importance for the electrode activity. As described in chapter 3.1, sPSU has a higher volume per weight unit. Therefore less sPSU ionomer for catalyst networking is necessary. The optimum for the Nafion® content is determined as 15 wt% in the anode. To optimize the sPSU content, anode polarization curves with 2 wt%, 5 wt% respectively 8 wt% sPSU were recorded (Fig. 6).

The anode with 5% sPSU shows the best performance at current densities above 200 mA cm^{-2} . Further investigations are necessary to specify more exactly the optimal ionomer content. It is to

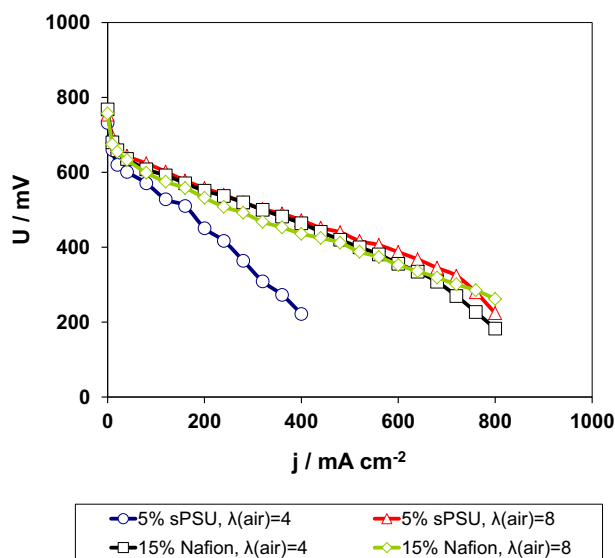


Fig. 9. Influence of the air stoichiometry on the MEA performance. $T = 130\text{ }^{\circ}\text{C}$, $A = 25\text{ cm}^2$, anode: 3 mg PtRu cm^{-2} , GDL: SGL 10BB, $\lambda_{1M\text{ MeOH}} = 2$, $p_a = 2.8\text{ bar}$; cathode: 1 mg Pt cm^{-2} , GDL: SGL 10BB, $\lambda_{\text{air}} = 4$.

Table 3

Collected water at the cathode outlet, $T = 130\text{ }^{\circ}\text{C}$, $A = 25\text{ cm}^2$, $j = 600\text{ mA cm}^{-2}$; anode: 3 mg PtRu cm^{-2} , GDL: SGL 10BB, $p_a = 2.8\text{ bar}$, $\lambda_{1M\text{ MeOH}} = 2$; cathode: 1 mg Pt cm^{-2} , GDL: SGL 10BB, $p_c = 4\text{ bar}$, $\lambda_{\text{air}} = \text{var.}$, 1 h operation.

	Cathode stoichiometry	Collected water, mL
Nafion®	4	45
Nafion®	8	45
sPSU	8	74

emphasize, that the presence of Triton X-100 in the anode catalyst layer can influence the MEA performance significantly (Fig. 10). When using the same sPSU dispersion, varying the sPSU content in the electrode in the range from 2 to 8 wt% causes a variation of the Triton X-100 content in the anode from 15 to 25 wt% respectively.

3.4. Anodic polarisation curves

As expected, the reaction rate of the methanol oxidation in a DMFC strongly depends on temperature [2]. Therefore, the activity of the sPSU anode rises with increasing temperature (Fig. 7). Further improved performance is expected for temperatures above $130\text{ }^{\circ}\text{C}$.

Fig. 8 shows a comparison of the polarization curves for methanol oxidation at a temperature of $130\text{ }^{\circ}\text{C}$ using different anode additives. It is evident that anodes bonded by 15% Nafion® are showing higher activity in the whole potential range than anodes bonded with sPSU. Changes of the interface caused by the Triton X-100 additive in the anode catalyst layer can influence the activity of the sPSU bonded anodes. Further optimisation of the sPSU and Triton X-100 content in the sPSU bonded anode is necessary.

3.5. DMFC full cell performance and methanol crossover

The performance of the MEA based on the 5 wt% sPSU and 20% Triton X-100 anode strongly depends on the air stoichiometry factor λ (Fig. 9). At a stoichiometry $\lambda(\text{air}) = 8$ it is comparable with the MEA performance having a Nafion® based anode. However, $\lambda(\text{air}) = 8$ is not suitable for practical operation.

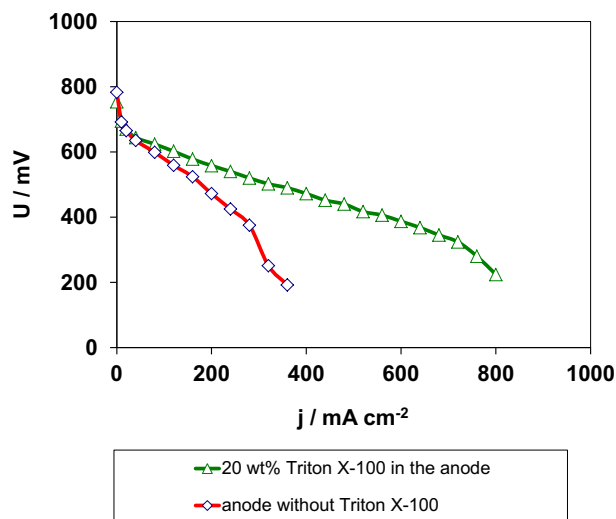


Fig. 10. Influence of Triton X-100 in the anode on the performance of a MEA based on a 5% sPSU anode. $T = 130\text{ }^{\circ}\text{C}$, $A = 25\text{ cm}^2$, Nafion® 115 membrane, anode: 3 mg PtRu cm^{-2} , GDL: SGL 10BB, $\lambda_{1M\text{ MeOH}} = 2$, $p_a = 2.8\text{ bar}$; cathode: 1 mg Pt cm^{-2} , GDL: SGL 10BB, $\lambda_{\text{air}} = 8$.

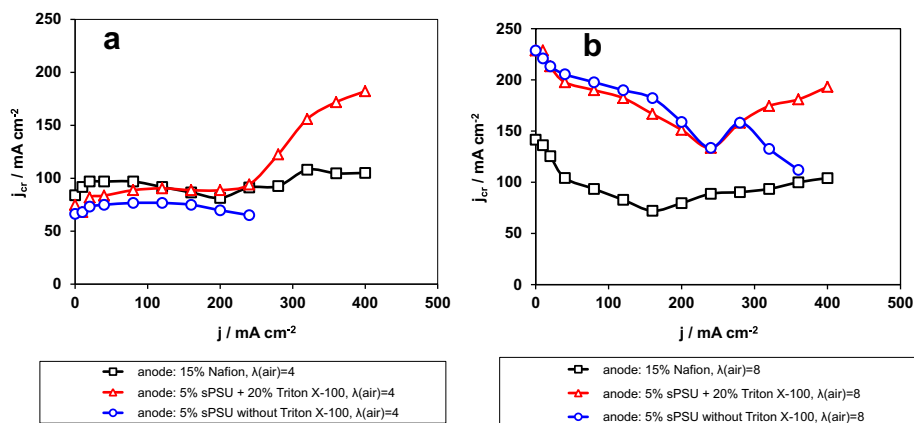


Fig. 11. Influence of the ionomer on the methanol crossover through the Nafion® 115 membrane. $T = 130^\circ\text{C}$, $A = 25\text{ cm}^2$, 1 M MeOH, anode: 3 mg PtRu cm^{-2} , GDL: SGL 10BB, $p_a = 2.8\text{ bar}$, $\lambda_{1\text{M MeOH}} = 2$; cathode: 1 mg Pt cm^{-2} , GDL: SGL 10BB, $p_c = 4\text{ bar}$, $\lambda_{\text{air}} = \text{var}$.

At $\lambda(\text{air}) = 4$ the performance of the MEA based on the sPSU anode is significantly lower as for the MEA with the Nafion® based anode. This effect relates probably to the cathode flooding because of the more permeable 5 wt% sPSU based anode. The Triton X-100 as non ionic surfactant might facilitate the transfer of water and methanol into the ionomer phase simultaneously promoting water and methanol crossover from the anode to the cathode. The resulting water (product water and water crossover from the anode) at the cathode outlet during 1 h operation with 600 mA cm^{-2} was measured. The results for MEAs with anodes based on 5% sPSU and 20% Triton X-100 respectively 15% Nafion® are compared in Table 3. The water amount for the MEA with sPSU and Triton X-100 in the anode is drastically increased.

As a result the oxygen transport to the cathode is decreased and the oxygen reduction reaction is hindered. Increasing the air flow removes the additional water from the cathode. The dependence of

the DMFC MEA performance from air flow and pressure was already described for Nafion® based MEAs [24]. Omission of Triton X-100 in a sPSU based anode strongly decreases the performance of the MEA (Fig. 10).

Apparently, the addition of Triton X-100 during anode preparation changes the overall transport properties in MEAs. The role of the additive and the detailed mechanisms are not yet fully understood. In any case, the performance of the entire MEA is significantly influenced by a surface active additive in the slurry used for depositing the catalyst layer. Beneficial effects were observed using a surfactant in the anode catalyst layer.

Methanol crossover, calculated by CO_2 evolution at the cathode, for the MEA with the sPSU based anode depends on the Triton X-100 content in the anode and the air stoichiometry (Fig. 11). As expected, at $\lambda(\text{air}) = 8$ by more dry cathode the methanol permeation is very high at open current voltage [7]. At small current densities

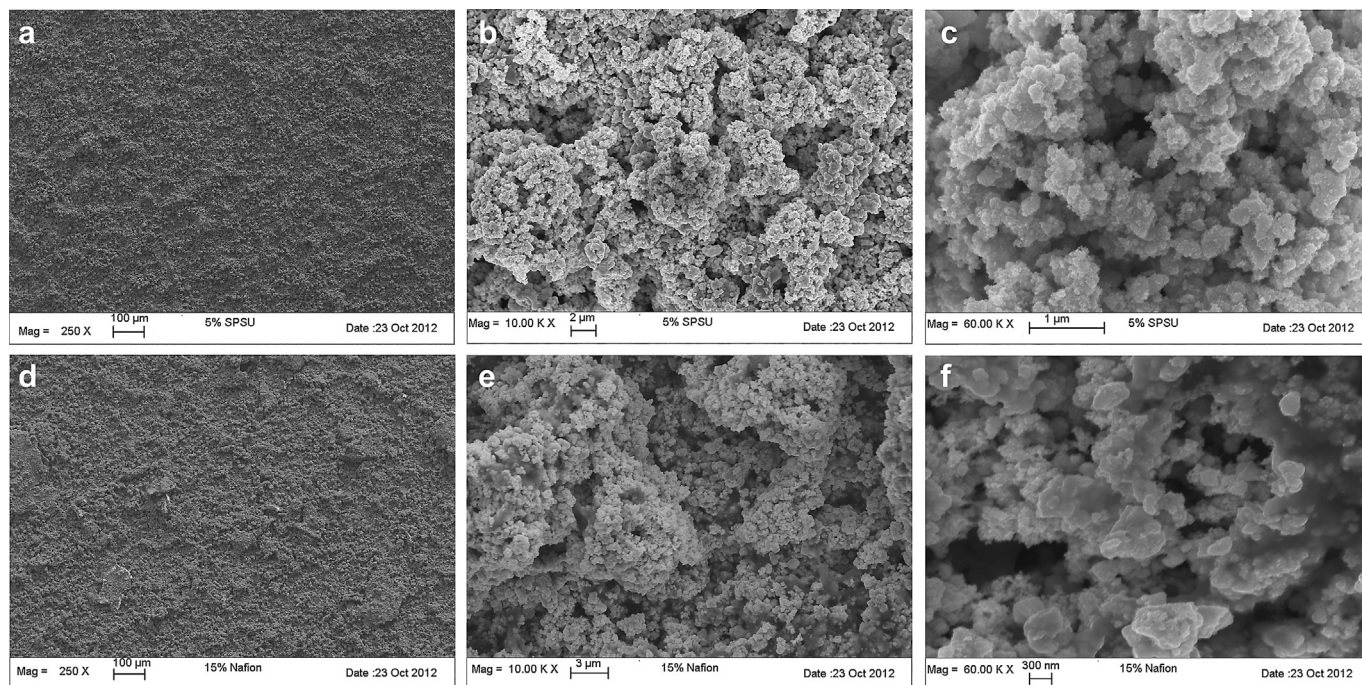


Fig. 12. SEM-Images of the surface of sPSU and Nafion® bonded anodes; magnification: 250 \times (left), 10,000 \times (middle), 60,000 \times (right); up: sPSU bonded anode, down: Nafion® bonded anode.

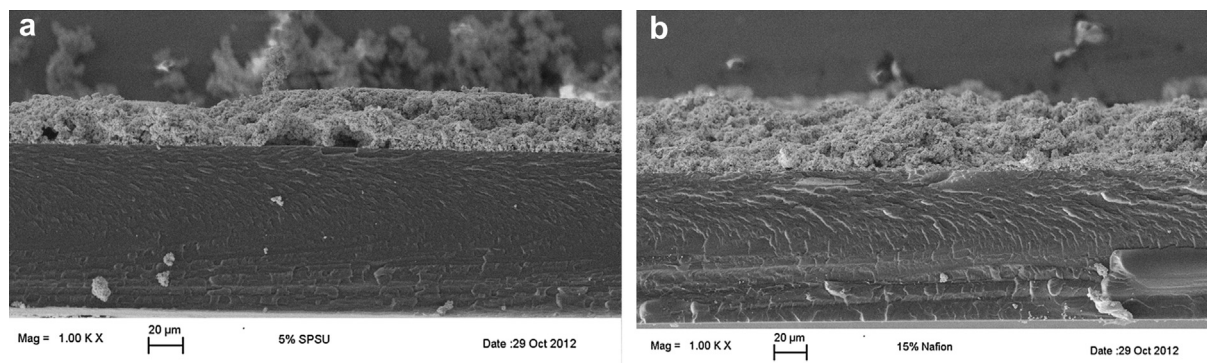


Fig. 13. SEM-Images of the cross-section of sPSU and Nafion® bonded anodes; magnification: 1000×; left: sPSU bonded anode, right: Nafion® bonded anode.

($j < 200 \text{ mA cm}^{-2}$) the methanol and air supply is at constant flow. The methanol crossover decreases until 200 mA cm^{-2} due to the decreased methanol gradient between anode and cathode by high methanol consumption on the anode. At higher current densities ($j > 200 \text{ mA cm}^{-2}$) the methanol and air supply are stoichiometric. The methanol crossover of the MEA with the anode based on sPSU without Triton X-100 is lower than for Nafion® based MEAs at $\lambda(\text{air}) = 4$ and decreases at higher current densities at $\lambda(\text{air}) = 8$. Further investigations are necessary to explain this effect.

The methanol crossover of the MEA with Triton X-100 containing anodes increases at higher current densities and is twice as high as for Nafion® based MEAs at 400 mA cm^{-2} . This effect can be related to effects of electro-osmotic drag. However, more detailed experiments quantifying the CO_2 release supported by modelling are needed to fully understand the effect. There is significant potential to influence the methanol crossover by optimising the Triton X-100 content in the anode, changing the cathode design or setup of a barrier layer on the cathode similar to that in Ref. [7].

This observation suggests that the surfactant Triton X-100 is opening the liquid pathways in the anode allowing more water and methanol to enter the electrolyte membrane and crossing over to the cathode.

Further investigations are necessary to determine the role and consequences of the Triton X-100 additive in the MEA. Probably the λ values can be decreased while still maintaining high power and

stable operating conditions by adjusting the Triton X-100 content in the anode catalyst layer or use of another GDL.

3.6. Morphology of the anodes

The sPSU bonded anode has a more homogeneous and denser structure than the Nafion® bonded anode (Fig. 12). The anode based on Nafion® has quite tall agglomerates on its surface and a more distributed pore structure due to the agglomerates inside of the anode. Nafion® forms a thicker film in the anode layer and therefore encloses more catalyst particles than sPSU. This is a possible explanation for the higher active surface area of the sPSU bonded anode (Fig. 5).

The adhesion between the sPSU bonded anode and the Nafion® 115 membrane is very good despite the different properties of sPSU as ionomer and the Nafion® membrane (Fig. 13). As expected, the adhesion between the Nafion® bonded anode and the Nafion® membrane is also very good. The thickness of both anodes is comparable.

3.7. Long-term stability

The long-term stability of the anodes was measured in a half cell setup (Fig. 14). The activity of the anode based on 5% sPSU and 20% Triton X-100 is lower, however the performance degradation is

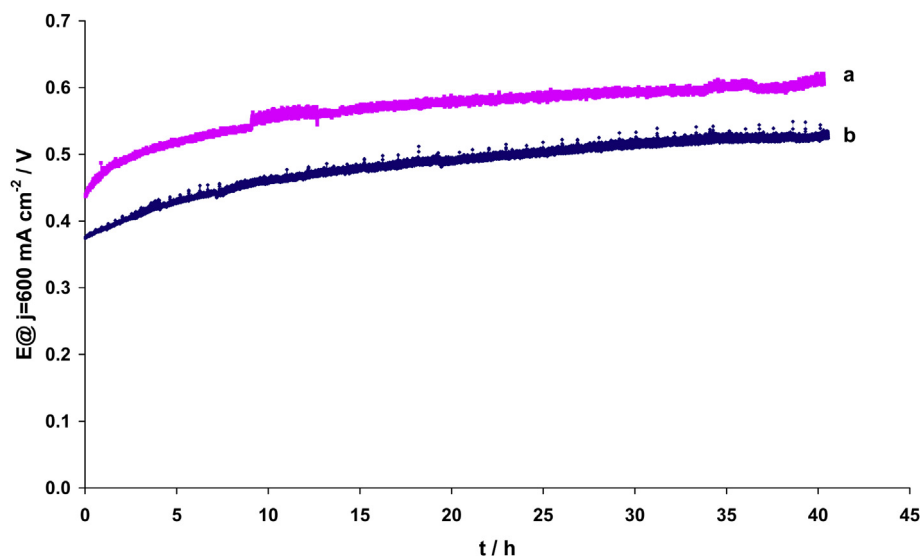


Fig. 14. Long-term test of a) a 5% sPSU anode or b) a 15% Nafion® anode; $T = 130^\circ \text{C}$, Nafion® 115 membrane, $A = 25 \text{ cm}^2$, $3 \text{ mg PtRu cm}^{-2}$, GDL: SGL 10BB, $\lambda_{1M} \text{ MeOH} = 2$, $p_a = 2.8 \text{ bar}$, half cell setup.

similar. The performance loss of both anodes is reversible. After a few minutes of operation at open current voltage, the initially voltage level is reached again.

4. Summary and conclusions

In this work, the sPSU polymer was investigated as an ion conducting phase in the anode catalyst layer. The activity for methanol oxidation of the novel anode based on sPSU is quite high, especially at high temperatures and current densities. The highest activity was obtained with 5% sPSU content in the anode.

The adhesion and the mechanical stability of the sPSU based anode on the Nafion[®] membrane are good at the operating conditions of a DMFC using an operating temperature up to 130 °C.

Anode catalyst inks based on sPSU do not require toxic and flammable solvents or dispersants. A harmless aqueous solution of the surfactant Triton X-100 or water is appropriate.

In this work, we could show that using the hydrocarbon based ionomer sPSU high performance DMFC anodes could be made. However, sPSU is not a suitable replacement for Nafion[®] yet. Further work will be dedicated to study sPSU-based electrodes applied to hydrocarbon membranes.

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